# Micromachined Pyro-optical Structure

**Descriptive title of the invention**: This invention describes a method of sensing incident radiation using a highly sensitive, thermal thin film structure. In its embodiment as an array, a thermal image obtained typically from infrared wavelengths is interrogated using an optical carrier beam and conventional CCD or CMOS imagers.

**Cross reference to related applications**: This application was originally filed as 60/249721 dated Nov 20, 2000 with the US Patent and Trademark Office.

**Statement regarding Fed sponsored R&D** Work leading to this invention was not funded by the US Government.

**Background of the invention**

Thermal-based sensor systems typically use a pixel that is highly sensitive to temperature differentials obtained by imaging various objects from a scene onto the thermal-sensitive pixel in order to cause local heating. This minute differential in temperature is read out using conversion techniques into an electrical signal.

The basic components for a thermal imaging system generally include ~~optical~~ means for collecting and focusing the incident irradiation from a scene onto an imaging focal plane. A chopper is often included in a thermal imaging system to produce a constant background radiance which provides a reference signal. The electronic processing portion of the thermal imaging system will subtract the reference signal from the total radiance signal to produce ~~a~~ an output signal with a minimum background noise level.

The concept of using a pyro-optical material as a sensor to detect radiation by modulating a carrier beam was first disclosed by Elliott in US Patent 4,594,507. This concept is cited as prior art in Fig. 1 which is an architectural representation of a system with an optical carrier source 1 and an external radiation source 2 illuminating a pyro-optical pixel 3 with a photodetector 4 to monitor the amplitude of the carrier source modulated by the transmissivity of the pyro-optical material. The concept of Fig. 1 has also been developed in various ways by the references cited. It is the purpose of the present invention to provide an improved sensor pixel based on the concept of Fig. 1. The present invention describes a micromachined pixel which contains a pyro-optical film and a resistive heater element integral ~~to~~ a thermally isolated platform above a temperature-referenced substrate.

The thermal imager of Elliott (US patent 4,594,507 ) includes a preferred embodiment of an optically active nematic crystal with a polarizer analyzer that is illuminated from an external light source of unspecified type. This thermal imager operates with an external

DATE SUBJECT

photodetector of unspecified type illuminated by the external light source through the nematic, temperature sensitive crystal. The result is an image converter operating with the nematic crystal as the modulator . The system detailed by Elliott operates within an oven typically at 28 deg C and is specified for imaging infrared irradiation only. Individual pixel structures are not disclosed or claimed and thus items such as separate pixel heaters and micromachined structures are not embodied in this invention. The Elliott system does not use compactness of construction since the external light source and photodetector are not integrated into the structure containing the nematic liquid crystal. Thermal isolation structures surrounding the nematic crystal film and any specific type of optical light source are not mentioned. Performance-enhancing interferometric structures are not mentioned.

Hanson in US patent 5,512,748 discloses a thermal imaging system containing a focal plane array in which a visible or near-infrared source is used to transfer an image from a transmissivity-modulated pyro-optical film layer onto an associated integrated circuit photodetector. The photodetector integrated into the substrate generate a bias signal representing the total radiance imaged from a remote low-level scene. A thermal sensor is described to contain infrared-sensitive material supported by two bifurcated support arms and nonflexing posts to maintain this film layer above the substrate with a gap therebetween. The thickness of the infrared-sensitive material is not mentioned except to note that it is preferably "very thin to enhance it's response to incident infrared radiation and to allow transmission of electromagnetic energy therethrough" (col. 7,line 8 ). The gap preferably corresponds to ¼ of the selected infrared incident radiation wavelength to

provide maximum reflection of the infrared from the semiconductor substrate to the infrared-sensitive film. Hanson does not disclose or claim the use of electrical heater elements or any means of temperature control within or without the infrared sensitive pixel. Hanson does not disclose or claim the use of vacuum surrounding the infrared-sensitive pixel. In addition Hanson does not disclose or claim the use of any thermally isolation media underlying the platform other than to describe a "gap" between the infrared-sensitive film and the underlying substrate.

Owen in US patent 5,087,661 describes a structure in with electrically conducting tetherbeams form a signal flow path for readout from a pyroelectric pixel material. The tetherbeams further provide a thermal isolation for the pyroelectric sensor microplatform

Ruffner et al in US patent 4,751,387 describes the use of a silica foam called aerogel as a solid, thermal isolation film formed between the pyroelectric capacitor and an underlying substrate as part of a specific infrared-sensitive pixel design without claims describing components external to the pixel. The use of pyro-optical sensitive materials is not disclosed or claimed. The Ruffner patent does not mention heating elements or ovens, vacuum conditions, the use of any optical carrier interrogation beams, pyro-optical materials, or the use of performance-enhancing interferometric structures.

Robillard in US patent 4,751,387 describes an infrared imaging system comprising a pyro-optic film consisting of dichroic liquid crystal coated on a membrane with a means of polarized visible light illumination onto the crystal film. In addition a means for

analyzing the polarization of the visible light carrier after reflection from or transmission through the crystal film is included in a system where the readout described is the human eye. Robillard does not disclose or claim any micromachined structures, thermal isolation structures, the use of partial vacuum, ovens, or pixel heaters.

Cross in US patent 4,994,672 describes an infrared imaging system including a sandwich structure of polarizing pyro-optic material formed over an optically transparent, thermally insulating foam such as silica aerogel. The reflectance (not transmission) of an interrogating light beam is modulated by the temperature of the material and is used to illuminate a pixel image onto a CCD. A container means is provided for enclosing the pyro-optical material and maintaining a stable temperature. The Cross system requires the use of polarized light and a system that does not utilize the polarization of light is not disclosed or claimed. Cross does not modulate the transmission of the interrogating optical beam. Cross does not disclose or claim the use of micromachined pixel structures, performance enhancing interferometric structures, vacuum conditions surrounding the pyro-optic material. Cross does not mention the use of insulating foam to thermally-isolate both sides of the pyro-optic material (only underneath).

Tuck in US patent 5,100,218 describes a specific thermal imaging system based on the thermal rotation of polarized light as it is modulated with transmission through a thermally-sensitive liquid crystal. The pyro-optical liquid crystal is separated from the optical source and photodetector by multiple lenses and thus is not a composite, sandwich structure integrating the optical carrier source and photodetectors. Liquid crystal is the

only pyro-optical material mentioned. Pyro-optical materials that do not require polarization are not disclosed or claimed. Tuck does not disclose or claim any micromachined structures, interferometric structures, any means of controlling ambient temperature, or operation with partial vacuum conditions.

Carr in US patent 6,091,050 describes a micromachined platform that elevates automatically and without continuing power requirement that is useful for implementing pixels in the present invention. The platform is elevated to a desired level as a result of design and manufacturing controls to create the desired vacuum or air gap between the pyro-optical film and the underlying substrate.

The described pyro-optical sensors are generally operated using a means of synchronously chopping the incoming low-level radiation to provide an image signal and a reference signal. Electronics for receiving the biased signal and the reference signal and for subtracting the reference signal from the biased signal to obtain an unbiased signal representing radiance differences emitted by objects in the scene is typically implemented in these systems. Carr and Sun in US patent 5,781,331 describe a micromachined shutter array that can serve as a means of synchronously chopping the incoming low-level radiation ~~for~~ with the present invention.

Hanson et al in 5,486,698 describe an actuation means for periodic thermal coupling of a bolometer or ferroelectric sensing platform to a thermal reference substrate. This actuator operates by electrostatic force which is derived from an external voltage source and eliminates the need for an external mechanical chopper.

**References Cited**

1.Charles T. Elliott et al, "Thermal Imager", US Patent 4,594,507 issued June 10, 1986

2. Charles M. Hanson, "Thermal Imaging System With a Monolithic Focal Plane Array and Method", US Patent 5,512,748 issued April 30, 1996

3. Robert A. Owen et al, "Thermal Isolation of Monolithic Thermal Detector", US Patent 6,087,661 issued July 11, 2000

3. Judith A. Ruffner, "Uncooled Thin Film Pyroeledctric IR Detector With Aerogel Thermal Isolation", US Patent 5,949,071 issued Sept 7, 1999

4. Jean J. A. Robillard, "Infrared Imaging System and Method", US Patent 4,751,387 issued June 14, 1988

5. Leslie E. Cross et al, "Pyro-optic Detector and Imager", US Patent 4,994,672 issued Feb 19, 1991

6. Amitava Gupta et al, "Broadband Optical Radiation Detector", US Patent 4,262, 198 issued April 14, 1981

7. Michael J. Tuck et al, "Thermal Imaging Optical System", US Patent 5,100,218 issued March 31, 1992

8. William N. Carr and Xi-qing Sun, "Optical Microshutter Array", US Patent 5,781,331 issued July 14, 1998

9. William N. Carr, "Thermal Microplatform", US Patent 6,091,050 issued July 18, 2000.

10. Charles M. Hanson et al, "Thermal Imaging System with Integrated Thermal Chopper", US Patent 5,486,698 issued Jan. 23, 1996

## Summary of the Invention

It is one object of the present invention to provide an improved uncooled, micromachined sensor pixel structure which utilizes a monolithic and self-aligned pixel which responds to thermal radiation. The visible or near infrared transmissivity or reflectivity of the thermally-isolated platform within the pixel is a parameter sensitive to temperature and therefore provides the means of detecting incident, absorbed radiation. The parameters of the pyro-optical film contained within the platform that are temperature sensitive are the optical index of refraction, bandgap absorption, and free carrier absorption.

One embodiment of the invention includes a resistive heater element within the thermally-isolated platform integral with the pixel maintains a nominal temperature which is modulated by absorbed, incident radiation. The embodiment with the resistive heater element integral with the platform also permits high speed thermal dithering to reduce the effects of thermal response hysteresis.

An advantage of the pixel is that no polarizing or extinction analyzers are utilized as optical components. An interrogating visible or near infrared light beam is modulated by the platform and signal readout is obtained using an ~~ancillary~~ underlying photodetector.

A further uniqueness of the invention is that the resulting modulation index of the signal readout for a given absorbed, incident radiation power is maximized by the use of films and structures forming a second Fabry-Perot sandwich structure integral to the pixel that enhance the absorption of the desired low-level radiation. The optical transmissivity of the pixel is configured geometrically with a first Fabry-Perot interferometric structure that further increases the index of modulation. The pyro-optical film itself is configured as a first Fabry-Perot sub structure with an optical thickness to maximize the index of modulation. The precise thickness optimum is a complex function of the pyro-optical film dielectric constant and the free carrier absorption at the wavelength of the low-level radiation. The pyro-optical film is typically of high index of refraction and is a primary controller of overall platform transmissivity to the optical carrier beam. The gap between the micromachined platform and the substrate mirror is also configured as part of the second Fabry-Perot sub structure to further increase the index of modulation by creating a node of maximum amplitude for the incident low-level radiation within the platform structure.

The pixel typically operates within a vacuum environment in order to provide adequate thermal isolation of the micromachined platform.

One embodiment of the present invention includes an optical ~~afocal~~ plane array having thermal sensors formed by a multiplicity of the pixels and with a high degree of reticulation between adjacent pixel platforms to minimize thermal spreading between adjacent pixel elements and to improve the spatial modulation transfer function of the resulting thermal sensors. Tetherbeams are used to support the platform structures above the substrate and with shared support posts to reduce the total array area and to increase the fill factor of pixel utilization. The pixel array processes a low-level image in parallel without the need for line and row scanning circuits within the pixel structures. The image formatting is accomplished by an underlying ~~ancillary~~ photodetector array which is typically a CCD or optical CMOS imager.

DATE SUBJECT PROJECT NO.

## Brief Description of the Drawings

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken with the accompanying drawings in which:

Fig. 1 is a block diagram representing the architectural functions of a pyro-optical sensor system based on modulation of the transmissivity of a carrier beam through a pyro-optical-film (prior art Elliot US Patent 4,594,507)

Fig. 2 is a cross-section schematic view of embodiment 1 a pyro-optical pixel with Fabry-Perot structures optimized for sensor performance in a specific infrared wavelength band

Fig. 3 is a cross-section schematic view of embodiment 2 three micromachined pixels with response optimized for three radiation wavelength bands: visible, 3-5 micrometers, and 8-12 micrometers

Fig. 4 is a cross-section schematic of embodiment 3 including 5 micromachined pixels positioned over a CCD or CMOS imager arranged to provide sensitivity in separate coplaner arrays for red, blue, green (visible), 3-5 micrometers, and 8-12 micrometers radiation wavelength

Fig. 5 Top view of an embodiment 4 containing an illustrative 4 x 4 pyro-optical pixel array with integral thermal dithering heater elements and shared anchor pedestal

Fig. 6 Top view of embodiment 5 containing an illustrative 4 x 4 array of pixels overlying the metallic reflector in configuration for electrostatic actuation of pixel for resetting the temperature of pixels to the substrate reference temperature. Pixel tether beams are flexible and ~~permit~~ actuate the platform to touch the substrate when the voltage is applied between the platform and the underlying metallic conductor





Sept 10, 2000

**Description of Preferred Embodiments**

In a first embodiment, an approximately collimated optical ~~beam from an external~~ LED beam 21 illuminates the first Fabry-Perot sub structure 31 of the pixel of Fig. 2. Also an infrared beam 22 of interest from an external source is focused onto the plane of the platform for processing by a second Fabry-Perot sub structure 23.

A first embodiment is shown in Fig. 2 which is a schematic cross-section view of a pyro-optical pixel with first and second Fabry-Perot structures optimized for sensor performance at specific wavelength bands for the optical carrier beam modulation and absorption of the low-level radiation, respectively. This cross-section shows two representative pixels positioned over a photodetector array 33. An optically transparent substrate 24 is either in the form of a starting wafer such as quartz or the transparent substrate is a film such as the standard passivation film or silicon nitride and silicon dioxide used to passivate the photodetector surface 32 with planarization processing well known to the art. Next a first metal fully reflecting film 25 of aluminum or gold is sputtered and lithographically ~~patterned on~~ the substrate to form the cross-section shown in Fig. 2. The first metal film ~~contains a~~ blocks the path for the externally-sourced light emitting diode beam to transit through to the underlying photodetector. Next a sacrificial film 26 is deposited and patterned over the first metal to form an underlying surface for the deposition of platform structural support and tetherbeams. The sacrificial film is typically high temperature polyimide or another polymer that is patterned to provide vias for the anchors for the platform structural support. Next the platform structural support 27 and tetherbeams 30 typically of LPCVD silicon dioxide are deposited at a maximum temperature of 350 deg C and patterned to define the platform and tetherbeams. Multiple depositions of tetherbeam films are ~~typically~~ deposited and patterned to achieve the desired elevation and thermal conductivity. A film of pyro-optical material 28 typically vanadium or vanadium oxide is deposited, patterned, and ~~oxidized~~ thermally processed appropriately over the platform structural support. The thickness of the vanadium oxide is optimized to provide for a maximum modulation index of the transmission of the LED beam though the pyro-optic film. The pyro-optic film is of high index of refraction and provides for example a quarter wavelength optical thickness for 800 nanometer photons when the vanadium oxide is approximately 85 nanometers in physical thickness. The thickness of the pyro-optical film 28 is the

primary determiner of the first Fabry-Perot structure modulation function. Over the pyro-optic film a partial transparency second metal film (29) is deposited and patterned using lift-off lithograph. An open area within the metal 2 pixel area is created by patterning to maximize the illumination of the pyro-optical film from the external LED. A sacrificial etch is now performed which removes all polyimide 26 that is accessible to an oxygen plasma etch process. The platform is thereby released and is mechanically coupled to the substrate only through the tetherbeams. The released structure is thermally isolated from the substrate.

A second Fabry-Perot structure 34 within the first embodiment is thus defined by the two metal films and the films sandwiched therebetween. The second Fabry-Perot structure is configured with controlled parameters being primarily the optical distance between the reflecting first metal and the second metal. An approximate separation of a quarter wavelength for the incident 10 micron wavelength low-level radiation is used, ~~This~~ requires a physical separation of 2 micrometers including the path through the pyro-optical film and the platform structural support. This second Fabry-Perot structure maximizes the absorption of the low-level radiation within the platform.

A second embodiment is described with a cross-section view of three pixels which are each tuned by the Fabry Perot technique for a different infrared wavelength sensitivity. The pixels are tuned using polyimide of three different thicknesses for the sacrificial layer as shown in Fig. 3. The second embodiment is fabricated similar to the first embodiment except that separate lithographic masking is used to etch back thick polyimide to the two thinner structures.

Polyimide is etched back using the oxygen plasma etch. The result is a three-pixel array that can be extended to thousands of pixels permitting imaging of a [illegible] source with three wavelength bands 34, 35, 36. The three wavelength bands are separated in the photodetector using temporal filtering or through the use of spatial addressing techniques within the photodetector array.

The concept of Fig. 3 can be extended to create a multiwavelength pixel array with sensitivities over multiple infrared and visible regions. Certain pixels can be designed to be fully transmissive to visible light or tuned to particular visible light wavelengths with the LED disabled. For operation of the pixel array ~~for~~ with visible imaging, the visible image is focused on the focal plane of the photodetector and is transmitted with a minimum of attenuation through the pixel platform structure. The infrared sensivitive pixels are fabricated the same as described in embodiment 2. Figure 4 shows a third embodiment where certain pixels are designed to exhibit maximum transparency to visible light 34 and other pixels are designed with second Fabry-Perot structures for maximum sensitivity to the infrared 34, 35, 36. The reflecting film 25 will block the LED carrier 21. Embodiment 3 permits a multispectral display of low level visible light from the readout of the photodetector array when the LED optical carrier source is disabled. If the photodetector readout is formatted as a monochrome array, then the 5 wavelengths 34, 35, 36, 37, 38 can be separated in time at the output of the imaging photodetector. Within a typical photodetector array there is not provision for separating the needed 5 different pixel transmissions and thus the wavelength response separation must be performed using a temporal filter at the output of the photodetector. An LED carrier beam is extinguished during exposure and readout of visible and uv wavelengths.

Heating elements are fabricated integral to the pyro-optic structure as illustrated by the masking pattern of Fig. 5 to create embodiment 4. This embodiment ~~can~~ be implemented as an add – on to embodiments 1, 2, and 3. The heating elements 51 are patterned onto the structural platform using a resistive film such as tantalum silicide, vanadium oxide, or tungsten silicide patterned ~~using~~ by means of a lift-off lithography. The electrical interconnections 52 to the external heater power source from the platform 53 are contained within the tetherbeams and consist of conducting ~~or partial~~ conducting patterned films. Embodiment 4 contains all of the process steps of embodiments 1,2, and 3 with the addition of processing to create the resistor heaters and interconnects. Tether-beams are anchored by means of the anchor pedestal 54. Optical beams illuminate the photodector array directly through orifice 55.

The pixels of embodiments 1,2,3, and 4 are typically suspended using tetherbeams that are horizontal with the plane of the substrate. There is a flexibility in these tetherbeams that permits them to move vertically with respect to the plane of the platform. This vertical gap is initially controlled through processing and the thickness of the sacrificial film. In a further embodiment 5 the platform can itself form an electrode of an electrostatic actuator with respect to an opposing metal electrode on the substrate When a sufficient voltage potential is applied between the two electrodes the platform is attracted to touch the substrate causing the platform temperature to equilibrate with the reference temperature of the platform. When the platform temperature is equilibrated to the reference platform temperature in synchronization with the frame rate of the photodetector imaging, then the need for an external radiation mechanical chopper is avoided. Typically mechanical choppers are used to establish a reference temperature for infrared imaging systems. This embodiment 5 of Fig. 6 is fabricated into individual pixels of

embodiments 1,2, and 3 as desired. Figure 6 shows the first metal reflector 61 with electrical contacts and a further electrical contact to the platform 62 conducting or semiconducting film thus providing an electrical connection to the two actuator electrodes 63. An external voltage source 63 is synchronously enabled to lower the platform into the physically – touching position . This platform does not operate with a rotational axis, but instead is a planer structure moving up and down as a parallel plate structure. The electrical connection to the platform electrode is obtained through an interconnect running along at least one tetherbeam 63 of each pixel. Embodiment 5 is made compatible with embodiment 4 by patterning the first metal into two interconnects for each pixel. The external voltage controller can control the heater temperature and the platform elevation simultaneously and independently using the split patterns of first metal.

Each embodiment forms a thermally-sensitive pixel that requires thermal isolation of the platform structure to obtain adequate thermal sensitivity. The pyro-optical structure is designed with thermal time constants in the range typically from 1 to 10 milliseconds. In typical vacuum operation the thermal time constant of the pixel is determined by the thermal mass of the pyro-optical structure and the thermal conductivity of the tetherbeams. In typical operation the pixel is operated in near vacuum conditions to eliminate the thermal effect of air ambient. The pixels of this invention can be designed for and operated in air ambient but with reduced thermal sensitivity.